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Technical Report 32-1216

Planetary Quarantine

Techniques for the Prevention of Contamination of the Planets by Unsterile Spaceflight Hardware

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Contents

Table

Figures

Contents (contd)

Figures (contd)

Abstract

System engineering techniques have been employed to: (1) identify possible sources of contamination; (2) develop required mathematical modeling; and (3) specify tests required to furnish experimental data for system trade-off studies. The mathematical models developed in the study have made possible several sensitivity simulations. These have indicated the importance of the contamination problem and have also pointed out areas where further experimental data or analytical work will be useful.

From this study, it will be possible to identify the most likely sources of contamination and to indicate corrective action. Knowledge from these studies can be applied to such questions as: (1) aim-point philosophy to be followed in the launch trajectory; (2) the need for decontamination or sterilization of the attitude control gas systems; (3) the recommendation of cleanliness levels during the manufacturing cycle; and (4) whether decontamination or sterilization will be necessary to achieve the required planetary quarantine goal.

Planetary Quarantine

Techniques for the Prevention of Contamination of the Planets by Unsterile Spaceflight Hardware

I. Introduction

A policy of planetary quarantine has been established to insure that no act will be performed during the period of planetary exploration that might spoil the scientific investigations of the planets. It is expected that these investigations will include the search for extraterrestrial life, and the collection of information leading to a better understanding of the origin of life. Provisions for the sterilization of all planetary probes or landers are included in the quarantine to prevent possible contamination that might interfere with attempts to determine the nature and existence of extraterrestrial life. Microorganisms could be deposited by an unsterilized lander, destroying future chances of determining if life forms have originated on the planet. In addition, the quarantine must be maintained for several years to allow for experiments sufficient to adequately define the planet's biosphere (Refs. 1–6).

The Committee on Space Research (COSPAR) of the International Council of Scientific Unions has formulated general recommendations for planetary quarantine (Refs. 7 and 8). In May 1966, the COSPAR Subcommittee for Planetary Quarantine recommended that the basic probability of 10^{-3} that a planet of biological interest will be contaminated during the period of biological exploration be adopted as a guiding criterion by all nations engaged in space exploration.

To meet this criterion, careful consideration must be given to the many possible sources of contamination that can be identified in the planning of a particular flight program, especially a program utilizing an unsterilized spacecraft for long-term orbit about a planet.

A typical flight program for the investigation of Mars during the 1970s has been recently defined (Ref. 9). The plan calls for two planetary vehicles to be launched from a single *Saturn V*. Each of the vehicles will be placed in orbit around Mars. After selection of a suitable landing site, each will eject a capsule for deorbit and landing. The spacecrafts will remain in orbit to perform various scientific experiments, and to serve as relay points for information from the separated lander capsules. Each capsule will incorporate entry and landing equipment, and a surface laboratory system for surface observations including biological experiments.

Noncontamination of Mars during the flights is a leading mission constraint. To make certain this constraint is fully considered during early engineering studies, system analysis techniques have been employed to identify all possible sources of contamination, and to evaluate these sources with respect to each other to insure that the mission can be accomplished without unduly penalizing any one portion of the mission. The purpose of this study is to describe the analysis techniques and experiments used, and to point out those sources that may be significant and worthy of detailed evaluation.

II. Sources of Contamination

To identify sources of contamination, it was first necessary to develop general constraint guidelines as a base of reference. The following guidelines were used for this study (Ref. 10):

(1) All aspects of the flight program, including the complex interactions of the spacecraft with the interplanetary environment, shall be examined to isolate every conceivable source of planetary contamination.

(2) Each separate source of contamination shall be investigated to yield an adequate understanding of the process through which it occurs. Whenever possible, mathematical models shall be formulated that adequately characterize the probability of contamination. These mathematical models shall be based upon standard probabilistic techniques, and the limitations and assumptions inherent in their formulation shall be explicitly described in the explanation of their validity.

(3) For those sources of contamination that can be adequately described by a mathematical model, formulae shall be propounded to calculate the probability of planetary contamination. Conservative assumptions shall be employed whenever uncertainties are present in the derivation of these formulae.

(4) Whenever an adequate mathematical model is impossible (for example, when the necessary assumptions are not meaningful), every effort shall be exerted to describe suitable ranges or bounds for the chances of planetary contamination.

Using these general constraint guidelines as a reference base, the following sources of contamination were identified for investigation.

A. Inadequately Sterilized Lander

(1) One or more viable organisms (VOs) remain on the outer surface of the lander capsule.

(2) One or more viable organisms within the capsule are released and diffused upon the planetary surface by

(a) Disintegration of the capsule upon impact.

(b) Erosion of the encapsulated areas.

B. Recontamination of the Sterile Lander

(1) Prior to launch by handling.

(2) During launch (for example, by breach of microbiological barrier).

(3) During interplanetary transfer by penetration of the microbiological barrier.

(4) During barrier release.

(5) After barrier release by unsterile debris.

(6) During capsule release (for example, by electrostatic attractions).

C. Accidental Impact of the Launch Vehicle or Parts of the Launch Vehicle

(1) Failure of the launch vehicle retromaneuver, or retromaneuver is of insufficient magnitude.

(2) Launch vehicle debris (for example, clamps, rings, and bolts) are placed on an impact trajectory.

(3) Launch vehicle detonates, scattering debris on an impact trajectory.

D. Accidental Impact of the Unsterile Spacecraft and/or Decay of the Unsterile-Spacecraft Orbit

(1) The spacecraft fails after injection into an impact trajectory.

(2) The spacecraft fails after being placed on an impact trajectory by the first or subsequent midcourse maneuvers.

(3) Large orbit determination errors (including errors in the astronomical unit and the Mars ephemeris) near the planet cause impact.

(4) Orbit insertion errors result in impact or rapidly decaying orbit.

(5) The nominal spacecraft orbit decays prematurely due to miscalculation of the Martian atmosphere.

E. Accidental Impacts of Various Standard and Nonstandard Spacecraft Ejecta

(1) Ejecta released during heliocentric cruise are placed on an impact trajectory.

(a) Attitude control gas.

(b) Spalling.

(c) Outgassing.

(d) Particles ejected by micrometeoroid impacts.

(e) Propulsion system exhaust gases.

(2) Ejected microbiological barrier is placed on an impact trajectory.

(3) Debris released at time of barrier separation are placed on an impact trajectory.

(4) Debris released at time of capsule separation are placed on an impact trajectory.

(5) Debris caused by detonation are scattered on an impact trajectory.

(a) Midcourse maneuvers.

(b) Orbit insertion maneuver.

(c) Capsule deflection maneuver.

(d) Abort rocket (if present).

(e) Pyrotechnics.

(f) Orbit trim maneuvers.

(6) Ejecta released during orbiting phase decay into the Martian atmosphere.

(a) Attitude control gas.

(b) Spalling.

(c) Outgassing.

(d) Particles ejected by micrometeoroid impacts.

(e) Propulsion system exhaust gases.

(7) Solar pressure eventually causes spinning that ejects debris, which decay into the Martian atmosphere.

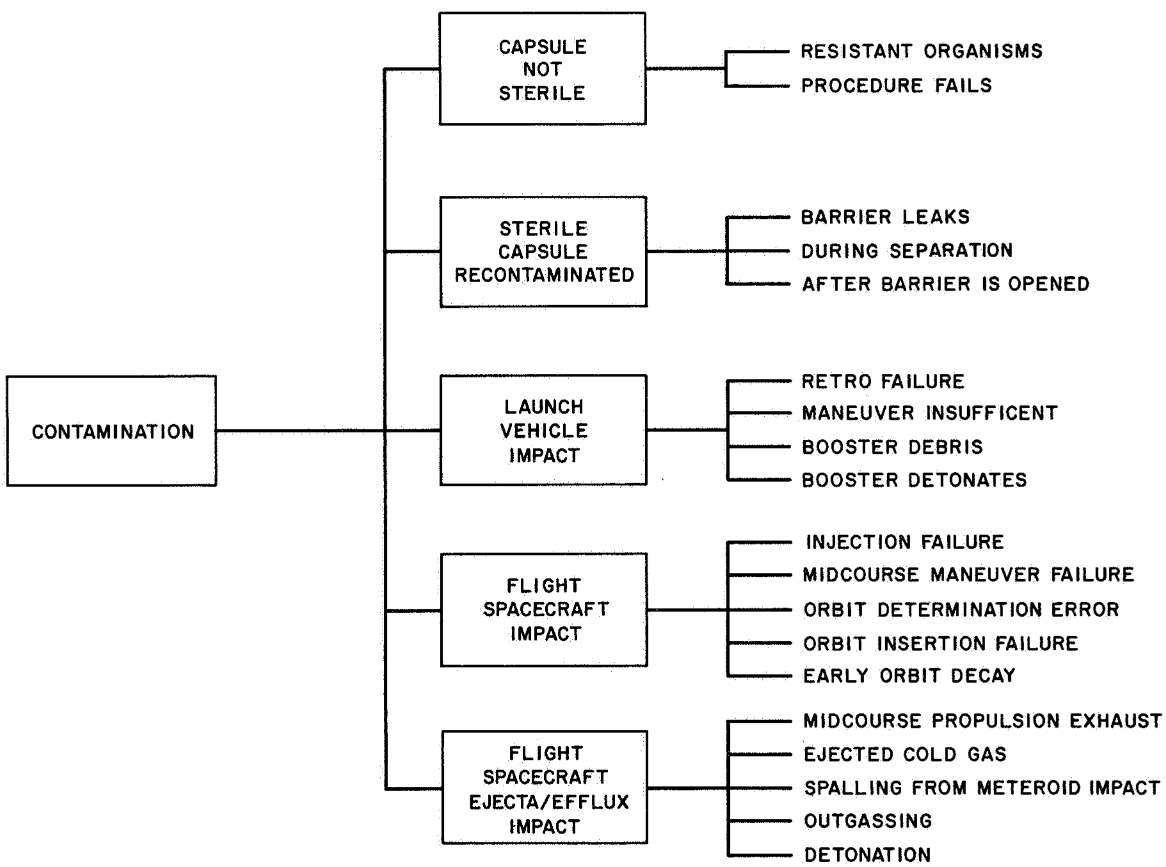

Fig. 1. Possible sources of contamination

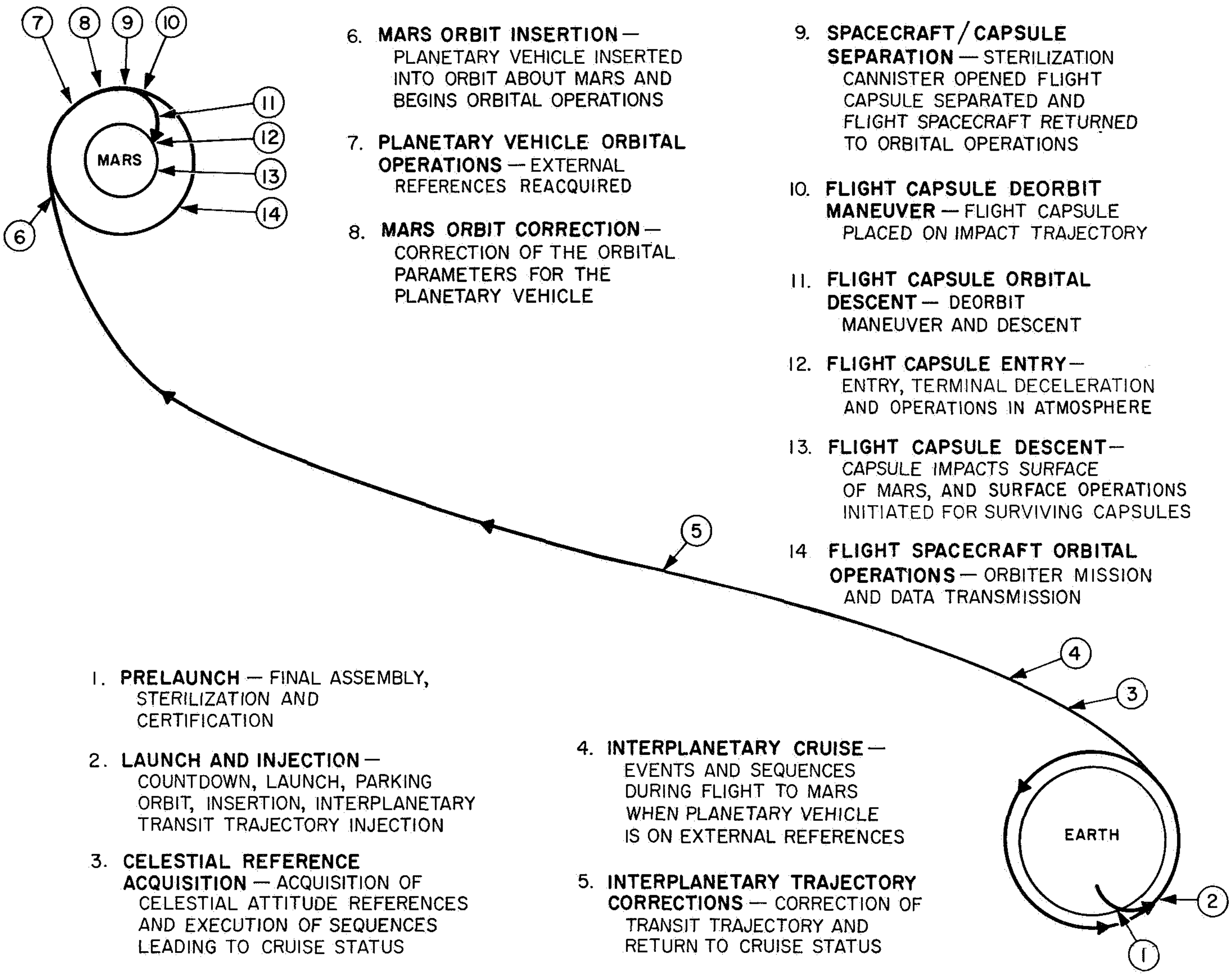

Fig. 2. Mission events in flight profile

The sources of contamination are summarized in Fig. 1; key mission events in the flight profile are shown in Fig. 2.

III. Mathematical Model

The mathematical model necessary to calculate the probability of contaminating Mars must, in effect, be a representation of the physical phenomena associated with the various contamination sources (Ref. 11). These physical phenomena can be grouped into three major elements.

The first element involves the number of viable microorganisms initially present in each source. The second element concerns the transport phenomena: the means by which these initially present microorganisms travel from the spacecraft to the Martian surface. The third element concerns the effect of various lethal environmental factors, or kill mechanisms, that tend to reduce the number of viable organisms.

Figure 3 is a matrix of the various specific elements in the mathematical model of this problem. For the purposes of this illustration, only four possible sources of contamination are listed. The numbered columns of the matrix (the specific elements) describe how particles might find their way to the surface of Mars and the effects of various lethal environments on these sources.

ROUTE TO MARS →

SOURCE OF CONTAMINATION	1 INITIAL VO LOADING	2 SURVIVE DURING TRIP	3 EJECTION PROCESS	4 TRANSPORT PROCESS	5 SURVIVE DIE-OFF	6 SURVIVE VACUUM	7 SURVIVE ULTRAVIOLET	8 SURVIVE OTHER SOLAR RADIATION	9 SURVIVE ENTRY HEATING	10 SURVIVE MARTIAN ENVIRONMENT	11 NUMBER VOs ON MARS SURFACE PRIOR TO TIME T
ATTITUDE CONTROL GAS SYSTEM											
ORBIT INSERTION ENGINE											
LOOSE PARTICLES											
MICRO-METEOROID EJECTA											

Fig. 3. Mathematical model format

The *first column* lists the number of viable organisms initially present in the contamination source. Column No. 2 lists the number surviving the approximate six-month transit to Mars. Column No. 3 represents the effect of the ejection process on the contamination source, and contains information of two types: (1) the rate at which microorganisms are ejected from the system, and (2) whether the microorganisms are killed in the process. For example, the second contamination source, the "Orbit Insertion Engine," involves ejecta that are subjected to temperatures of approximately 6000°F for several milliseconds. The entry under "Ejection Process," then, is simply the probability of microorganisms surviving these temperatures and time durations.

Column No. 4, concerns the probability of survival during the transport process. This entry involves the orbit mechanics related to the gas molecules and microorganisms that leave the system at various velocities and in various directions in space. The fraction of these organisms and the gas molecules actually placed on a Mars impact trajectory is indicated.

Columns 5, 6, 7, and 8 list several possible kill mechanisms. Column 9 contains the calculations concerning the effect of atmospheric heating on viable organisms as particulate material enters the Martian atmosphere at high velocity. Column 10 provides for a "growth and contamination" factor as determined at the May 1966 COSPAR meetings, and discussed on page 1 of this report. Finally, Column 11 contains the total probability of contamination from a particular source; the sum of Column 11 is the total probability of contaminating Mars from all sources for the given mission under study.

A series of computer programs were developed that essentially perform the mathematical analysis represented by the matrix shown in Fig. 3. Initially, the question arose as to whether the analysis should be based on average values, that is, the average number of microorganisms that might be expected in a given contamination source. Such an approach was discarded because average values would be used for input information, resulting in an answer in terms of the average. A second method considered was to work with maximum, or worst case data (that is, the maximum possible number of organisms in the contamination source). This approach was also discarded because the final result would be a worst case number, hence, an unrealistic one.

The approach chosen as most realistic was to formulate the input information into probability distributions. Figure 4 illustrates an initial microbial loading distribution presented in terms of probability. Probability P_1 represents a certain chance that between 0 and 10 viable organisms are associated with the particular source. P_2

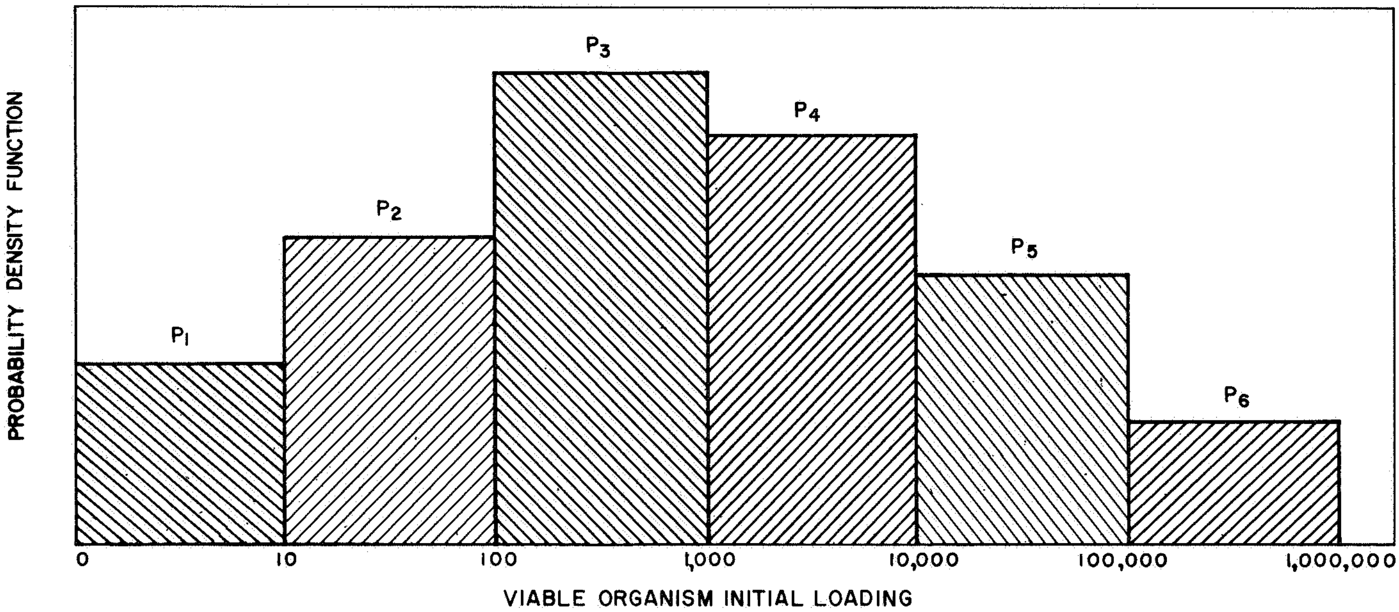

Fig. 4. Input data format

through P_6 represent different probabilities carried out to the last significant interval. Similarly, various input information necessary throughout the analysis was in most cases represented as distributions. For instance, to perform the orbit mechanics analysis on ejected particles, it is necessary to have input information on the source of the particles, their size, velocity and trajectory. An example of the resulting distributive-type output is shown in Fig. 5.

An example of the detail contained in the analysis and the nature of the input and output information obtained from one column can be seen in Fig. 6. The heliocentric portion of the orbit mechanics is indicated on this chart. The spacecraft is located at any point in the transfer trajectory from earth to Mars. An impact plane is shown with Mars located relative to the coordinate axis, which represents the aim point of the spacecraft trajectory. The input information used in this program is shown at

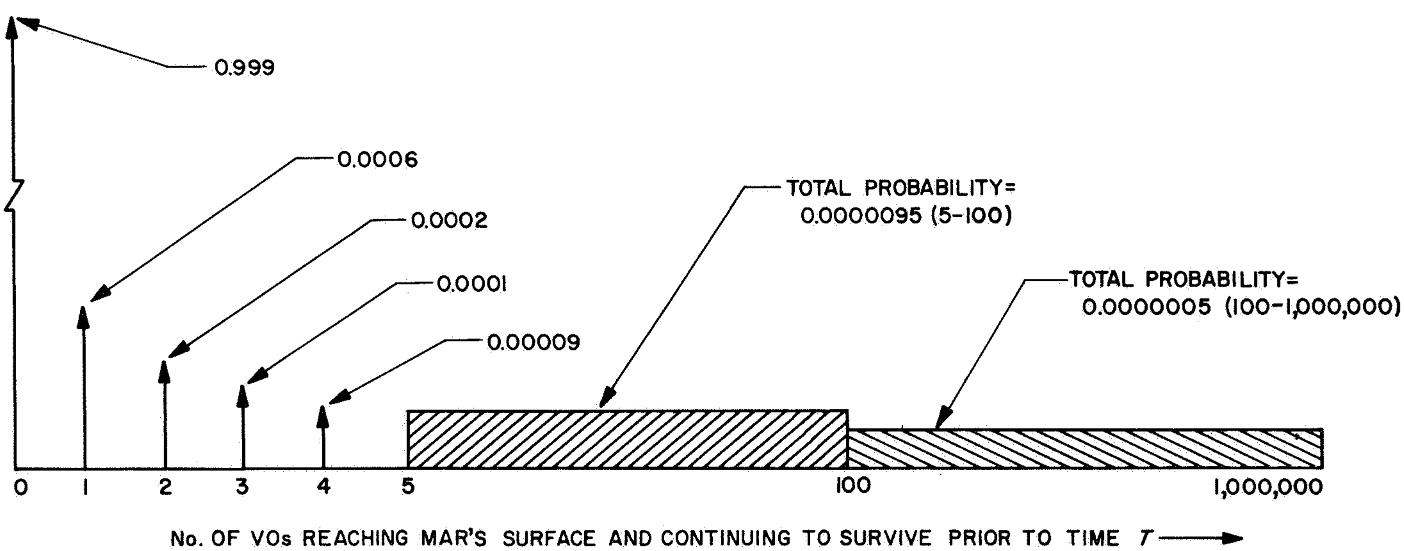

Fig. 5. Typical distributive output format

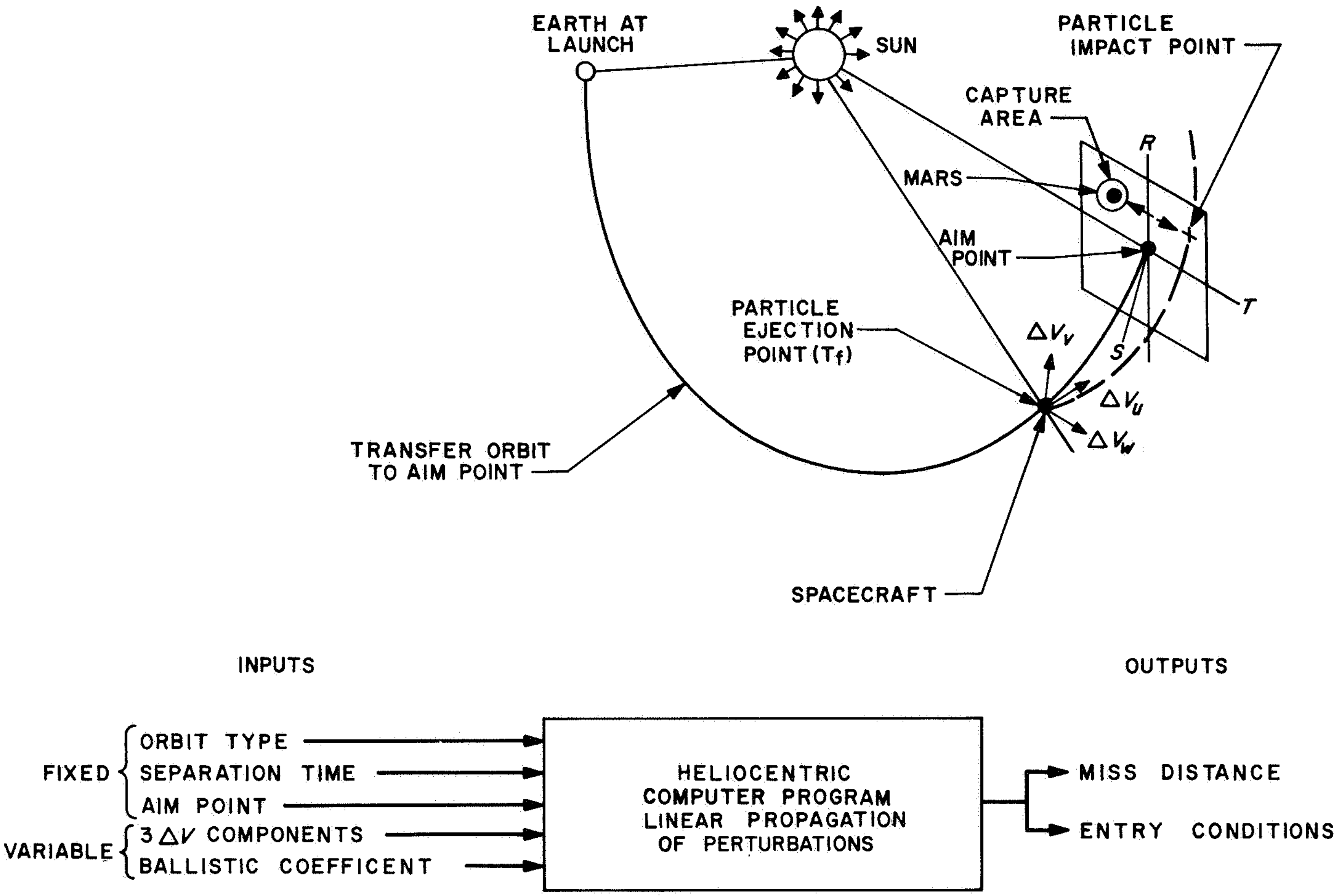

Fig. 6. Orbit mechanics for heliocentric trajectory

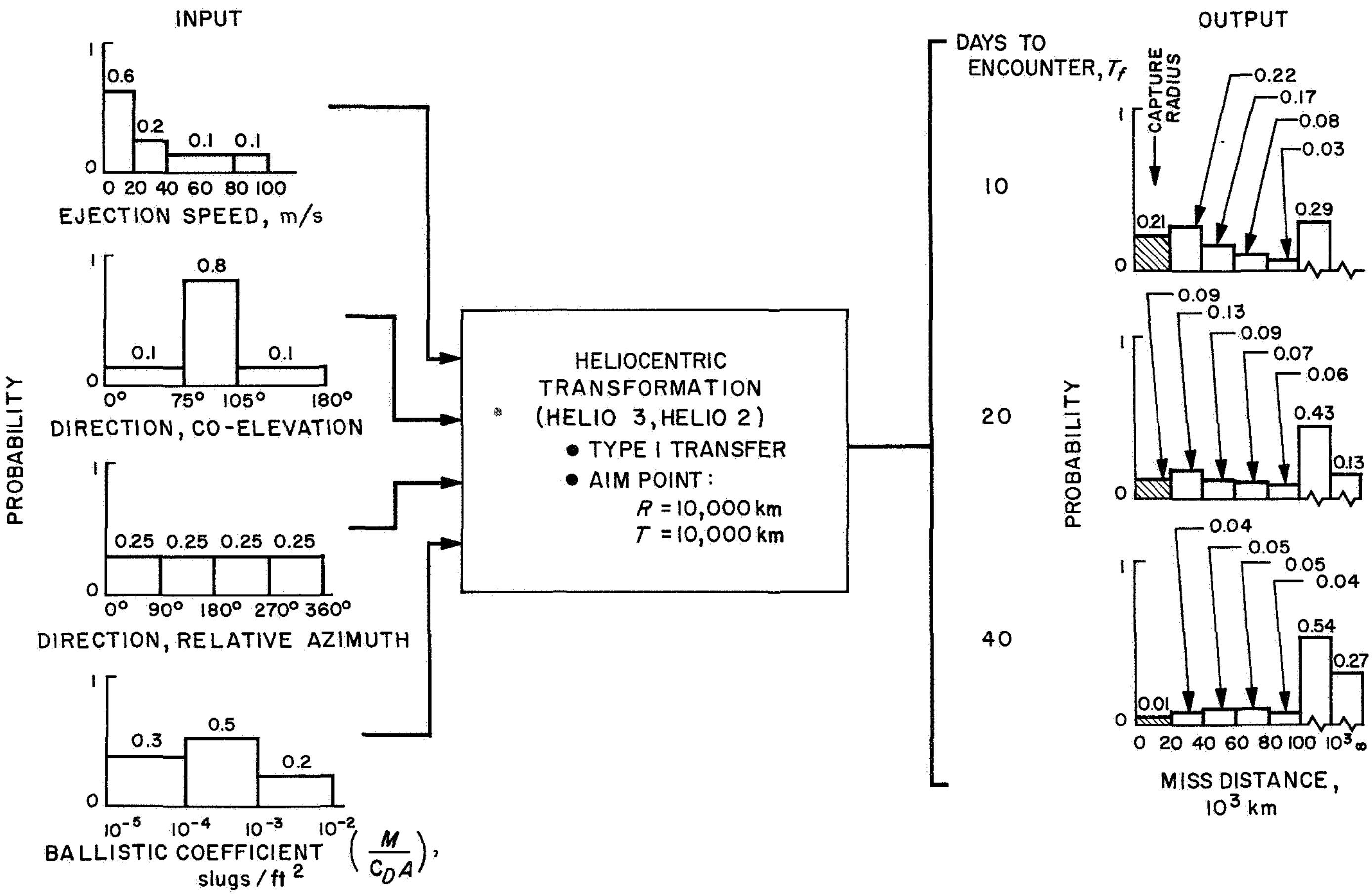

Fig. 7. Typical heliocentric orbit mechanics data

the bottom of the figure; it consists of the type of transfer trajectory, the coordinates of the aim point, the number of days prior to Mars encounter, the speed of the particles, direction of the particles, and finally information on the ballistic coefficient which, in effect, is size information. Figure 7 illustrates how the parameters of speed, direction, and size are used as input distributions. Similarly, the output for miss distance is shown in distribution format.

Another example of a major analytical effort contained in the computer analytical model is seen in Fig. 8, which shows a time vs temperature profile of a specific small particle calculated for three entry angles. The many variables required to calculate just one time vs temperature profile for a single particle as it enters the Martian atmosphere are also listed. The program used two different atmospheres to study the effect of the atmosphere definition, and was able to accept distributive-type input information on velocities, direction in space, ballistic parameters, and emissivity.

IV. Tests and Experiments

In addition to the major parametric analyses and the various computer programs made available by the mathematical model, input information on the many contamination sources to be studied was necessary. Many of the problems concerning these sources have not been previously investigated, and a great deal of the input information did not exist at the initiation of this study. Consequently, a series of experimental programs were conducted, aimed at yielding insight into these problems, and particularly at obtaining experimental data to be used as input information in the contamination analysis.

A. The Orbit Insertion Engine

The largest of these experimental efforts concerns the orbit insertion engine used during the Mars mission. Because the engine is extremely large (on the order of 10,000 lb) and might be fired close to Mars, it is very important to determine whether the engine poses a contamination threat. Solving the problems associated with

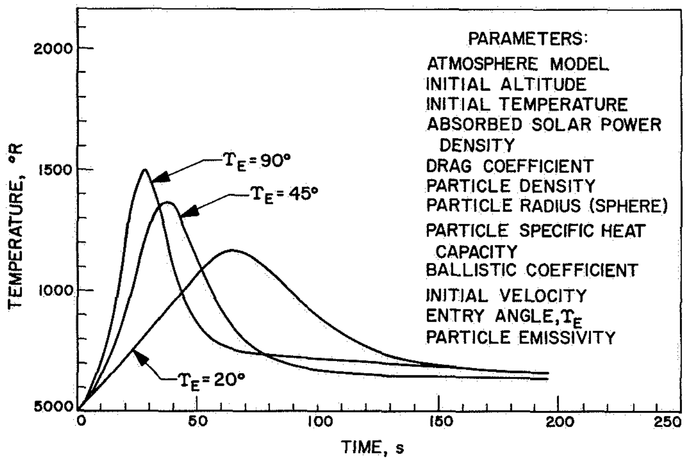

Fig. 8. Particle temperature histories

sterilization of the engine, if sterilization is proven necessary, requires a significant engineering undertaking. The experimental effort consisted of a thorough preliminary feasibility study, followed by the design and initiation of a test program using three types of small engines: solid, monopropellant liquid, and bipropellant liquid (Ref. 12). A known number of microorganisms were inoculated into an engine, which was then fired into a test chamber. After the firing, the chamber was bioassayed to determine the number of viable organisms present. The equipment used for these tests is illustrated in Fig. 9. For the test to be meaningful, many factors had to be carefully analyzed before the actual combustion firings.

Figure 10 indicates dwell time vs temperature, an important relationship subject to control. Both the calculated time-temperature of the real solid motor, and the calculated time-temperature to be simulated with the test engine and the heat chamber are shown. Twenty-two test firings of development engines were undertaken to verify and control the time–temperature simulation for all the engines.

B. Bioassay Procedures

Another major factor affecting the validity of the test results concerned the bioassay procedures. A series of tests were undertaken to develop and calibrate reliable bioassay recovery procedures before the actual test firings were undertaken.

C. Ejecta Size

A second major experimental program was undertaken to determine the size of the ejecta leaving the spacecraft when impacted by a micrometeoroid. Information was also desired on how many ejected viable organisms might be killed by the micrometeorite impact process and how many would remain alive and on a path toward Mars.

A micrometeoroid simulator facility capable of firing 5-μm particles at an average velocity of 30,000 ft/s was used for this program (Ref. 13). A schematic diagram of this facility is shown in Fig. 11. An explosive charge shown at the top of the figure was detonated to send small micron-size iron particles through the vacuum region in the middle into the target area or trap located at the bottom of the apparatus. Targets were inoculated on the top and bottom with a known number of microorganisms and placed in the center of this trap. A gelatin catcher medium was located above and below the target. After the firing, the entire micrometeorite trap was removed to a biological laboratory, disassembled, and bioassayed. Figure 12 indicates the type of information obtained for the size distribution of the ejecta. Table 1 lists typical materials used on a spacecraft, including the four that were selected for testing. The initial phase of the program consisted of more than 40 test firings as the apparatus and the bioassay procedures were developed. The final test program involved a matrix of tests for the four major materials tested. The tests

Table 1. Spacecraft materials

Material	Alloy	Thickness, mils	Surface area, ft^2
Aluminum[a]	2024-T4	3–65	1651.3
Aluminum	Mesh	10	6.7
Aluminum	7075-T6	10, 60	22.3
Aluminum[a]	6061	40	713.0
Magnesium	HM21A-T8	60	17.3
Magnesium	ZK60A-TS	65	50.0
Stainless steel	(Haynes alloy)	45	4.3
Honeycomb	(Phenolic)	0.25 in.	56.3
Honeycomb	(Aluminum)	0.64 in.	24.0
Fiberglass—epoxy sheet[a]	(Textolite)	17	226.0
Solar cell coverglass[a]	(Fused silica)	10	226.0
Electric cabling		10	3.0
Silica phenolic tape with graphite		>100 >200	36.7 5.3

[a]Selected for testing.

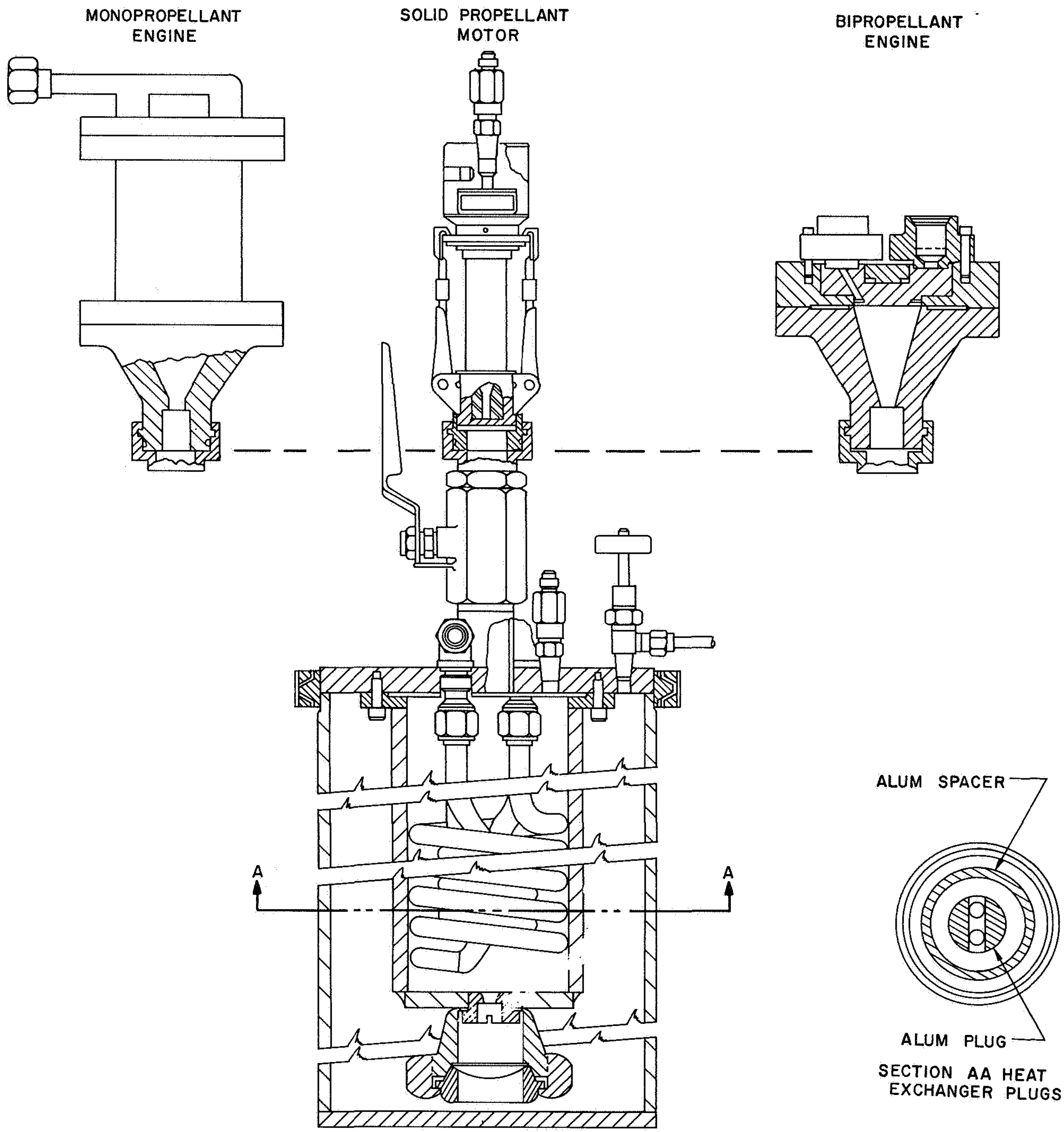

Fig. 9. Combustion lethality equipment

consisted of three levels of inoculation, and four replicate tests at each point for the four materials.

D. Manufacturing Debris

Another area where very little data were available concerned the mechanism of various loose particles deposited on the spacecraft during the manufacturing cycle that would be free to leave the spacecraft during the mission and carry viable organisms, as passengers, to Mars. Analysis of this problem required information on the number of particles that might accumulate on the

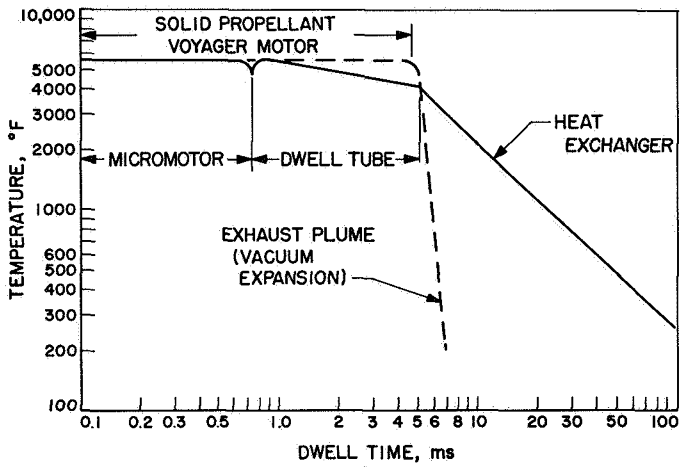

Fig. 10. Combustion lethality equipment simulation of heat exposure for solid motors

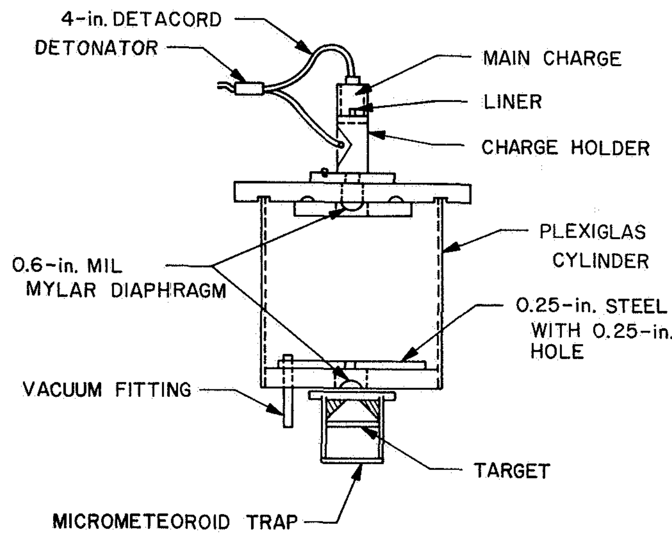

Fig. 11. Microparticle projector

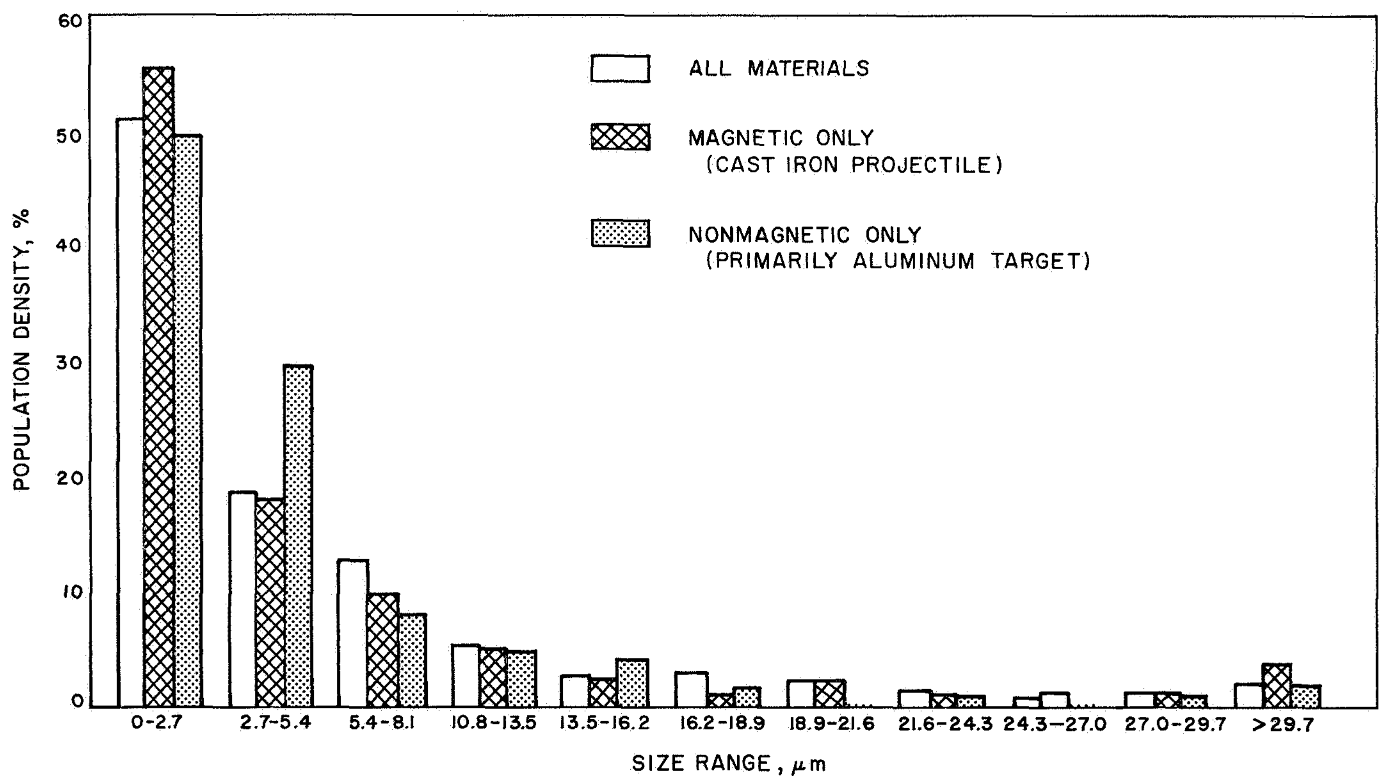

Fig. 12. Micrometeoroid ejecta size distribution

spacecraft and their size distributions. A program was undertaken that included data from existing spacecraft programs (*Nimbus*). The available data on certain particle size ranges and on spacecraft cleaning methods were reviewed and summarized. In addition, new information was obtained on the smaller size ranges. Figure 13 shows the particle size vs distribution for several of the programs surveyed.

E. Attitude Control Gas System

An experimental program was also conducted on the attitude control gas system as a contamination source (Ref. 14). A scaled-down model of a spacecraft attitude control system was fabricated. Special filters were developed to cover the nozzle, and a series of typical Mars-mission firing sequences were carried out. The output from the filtered nozzle was collected and bioassayed. After a full test sequence, the entire system was installed on a vibration fixture and vibrated at a rate equivalent to the launch vibration level. The full test sequence was then repeated to determine whether vibration released viable organisms within the system to be expelled with the gas. In addition to the work on this engine, some tests were performed on an existing *Nimbus* spacecraft attitude control system.

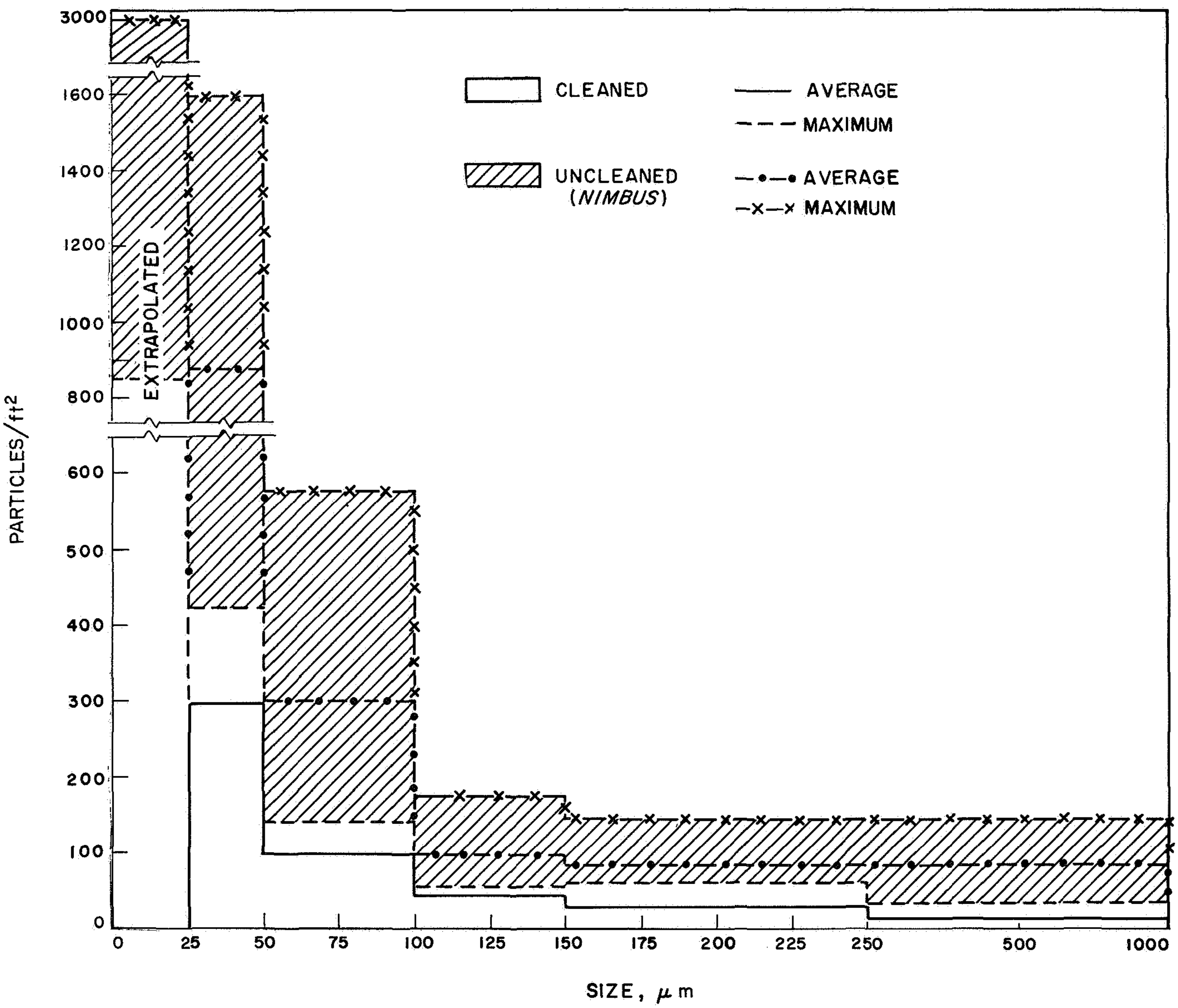

Fig. 13. Loose particle size distribution (manufacturing disposition)

F. Unprotected Microorganisms in Space

It is likely that the space environment could affect the rate of die-off of unprotected microorganisms. To evaluate this rate of die-off, a series of tests have recently been undertaken in a space simulator. These tests were designed to delineate the individual and combined effects of ultra-high vacuum and temperature on the viability of *B. subtilis* variety *niger* spores, using thermal-vacuum relationships previously observed with the *Mariner IV* solar panels during the interplanetary cruise to Mars (Ref. 15). The space simulator used was a spherical high-vacuum chamber capable of pumping to 10^{-10} torr. A molecular trap within the chamber provided up to 99.97% capture of condensable molecules escaping from the test specimen. The various tests included exposure at temperatures ranging from 22 to 60°C.

Results indicate a significant die-off of unprotected microorganisms during exposure to the simulated space environment. Further tests and statistical analysis of the data are required to validate and quantitate the results.

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